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Support requirements in rockburst conditions*

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SYNOPSIS

The support of stopes and tunnels in South African gold mines subject to rockburst damage requires special attention. The interaction of a seismic wave with either a stope or a tunnel is subject to a number of variables, namely the distance from the source of the event, the ground velocity, the orientation of the excavation with respect to the direction of the seismic wave, and the geology and fracturing around the excavation.

This paper discusses these factors in relation to the support requirements in stopes and tunnels. The need for the integration of hydraulic props with stope support and the use of yielding anchors for tunnel support are emphasized.

SAMEVATTING

Die bestutting van afbouplekke en tonnels in Suid-Afrikaanse goudmyne wat aan skade as gevolg van rotsbarstings onderhewig is, vereis spesiale aandag. Die wisselwerking tussen 'n seismiese golf en 'n afbouplek of 'n tonnel is aan 'n aantal veranderlikes onderhewig, naamlik die afstand vanaf die bron van die gebeurtenis, die grondsnelheid, die oriëntasie van die uitgrawing ten opsigte van die rigting van die seismiese golf, en die geologie en breuke om die uitgrawing.

Hierdie referaat bespreek hierdie faktore met betrekking tot die bestuttingsvereistes in afbouplekke en tonnels. Die noodsaaklikheid van die integrering van hidrouliese stutte met afboubestutting en die gebruik van meegee-ankers vir tonnelbestutting word beklemtoon.

Introduction

In South African gold mines, the walls of a mining excavation are supported to allow mining operations to take place safely within the excavation throughout its serviceable life. The support requirements vary according to the anticipated useful life of the excavation, to the size and shape of the excavation, to the magnitude and change in stress it will experience, and to the geology of the area. In addition, special precautions should be taken if the excavation is likely to experience a rockburst.

This paper briefly explains the mechanism of a rockburst and goes on to describe the effects that rockbursts can have on the support systems for stopes and tunnels. In each case, the basic support requirements are described before the requirements for rockburst conditions are considered.

Rockbursts

Types of Rockbursts

Salamon has described a rockburst as a subset of seismic events. Therefore, a rockburst is a seismic event that causes damage to an excavation. It is useful to distinguish between the seismic event itself and the damage that it produces. Seismic events are almost always associated with shear displacements on fractures or geological weaknesses. Even events that appear to be exceptions to this rule, such as the sudden crushing of an isolated pillar or the sudden crushing of rock on a stope face, can be resolved into a set of simultaneous shear–slip movements within the crushed rock. An understanding of the shear–slip phenomenon is thus fundamental to the study of rockbursts.

During a dynamic fault slip, elastic waves are generated that are propagated through the rockmass. These elastic waves occasionally cause damage when they encounter a mining excavation, resulting in a rockburst. In addition, the slip displacement produces a static stress change that can affect excavations sufficiently close to the event by a simple increase in field stress.

Wave and Particle Velocity

The velocity at which a compressional seismic wave is propagated through intact quartzite is about 5,4 km/s. Shear waves travel more slowly, at 3,7 km/s. However, the velocity attained by particles within the rockmass is seldom more than a few metres per second. There is thus a difference of about three orders of magnitude between the particle velocity and the wave-propagation velocity. This observation has an extremely significant consequence for the design of support, as will be demonstrated later. Because of the large difference in scale between the 'energy-containing' seismic wavelengths and the size of a typical mine tunnel, it is possible in principle to design the support system required to hold the fractured rock around a tunnel in place. However, in the case of a stope, certain additional simplifying assumptions are required.

Another way of viewing the effect of a seismic wave on support is to consider a compressional seismic wave schematically superimposed on a tunnel as in Fig. 1. As can be seen in this diagram, the wavelength of a typical seismic compressive wave is considerably longer than the size of the tunnel. Reading directly from Fig. 1, one can see that, at a given time, all the particles in the immediate vicinity of the tunnel are moving at essentially the same velocity. This means that there is no dynamic amplification of stresses in the rock due to the presence of the

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tunnel[1]. Within the period of the wavelength of a typical compression wave, the whole tunnel is displaced in one direction, and then moves back to its original position. Stopes are more complex, since a stope is often of a size comparable with that of the wavelength of a typical seismic wave.

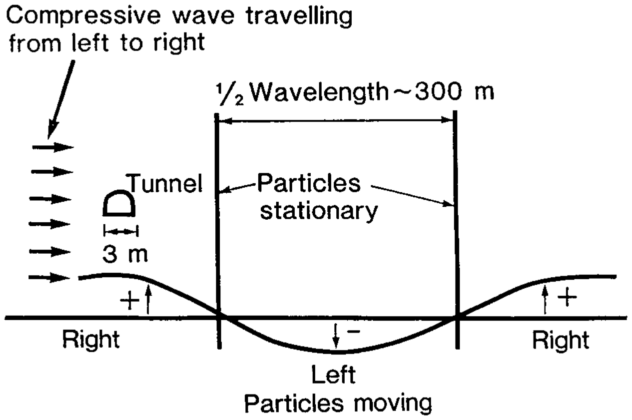

Fig. 1—Schematic diagram of a compressive seismic wave superimposed on a tunnel

It is thus possible in principle to design support for the dynamic stresses.

The Stoping Environment

The rock surrounding a stoping excavation at depth is intensely fractured, and the fractures extend several metres into the hangingwall and footwall (Fig. 2). The fractures strike in the approximate direction of the face and have a near vertical dip. Parallel to the reef are bedding planes that have a variable frequency of occurrence above and below the stope. The cohesion on these bedding planes is also variable. Dykes, joints, and faults are other planes of discontinuity within the rockmass.

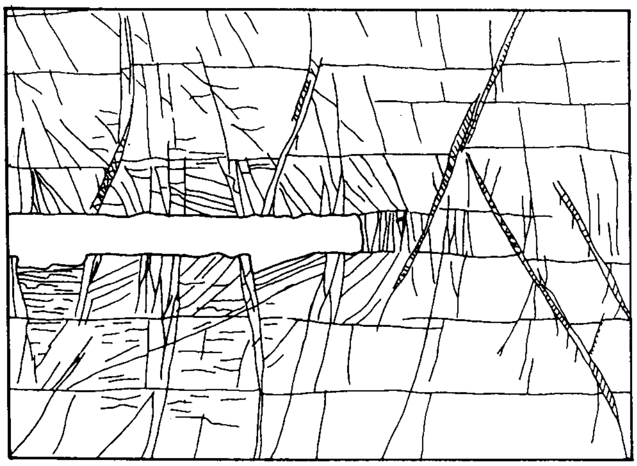

Fig. 2—A section showing fracturing around a deep stope

As the stope face advances and the stope span increases, the hangingwall and footwall converge. This convergence is caused by the elastic response of the rockmass, as well as by the inelastic deformation of the fractured rockmass, into the stope excavation. The inelastic deformation, particularly bedding separation, is not fully understood but can contribute a significant amount of the closure that occurs in a stope. Friction between blocks of hangingwall under the action of compressive horizontal stress caused by dilatation of the fractured rock ahead of the face usually ensures that the integrity of the hangingwall is maintained. However, unfavourable fracture orientations or friable hangingwall material can affect the stability of the hangingwall.

The support system in a stope must be able to accommodate the stope closure, support the fractured hangingwall, and ensure a safe working environment in the vicinity of the face. In the event of a rockburst, the support system may be subjected to large rapid deformations, and in this process it must be able to absorb energy in decelerating the blocks of fractured rock.

The Effect of Rockbursts on Stopes

Wagner[2] has suggested the following analysis for the processes that occur during a rockburst. For the purposes of demonstrating the principles involved, the following simplifying assumptions are made.

(a) The seismic event occurs some distance away in the hangingwall above a stope.
(b) This seismic event radiates a compressional wave that impinges on the loose hangingwall rock in a downward direction.
(c) The blocks of rock in the hangingwall are supported by some form of support system in the stope.

The phenomena that occur as a compressional wave reaches a hangingwall are illustrated in Fig. 3.

In Fig. 3(a), a layer of loose hangingwall rock of height h is accelerated to velocity v by the rising front of the compression wave. This loose rock thus possesses kinetic energy since it has a mass m and is travelling at velocity v. Without support, the loose rock would break away from the solid hangingwall and impact against the footwall during the receding part of the compressional wave. However, with good support, this kinetic energy, $\frac{1}{2} mv^2$, can be absorbed by doing work on the support as the support yields.

In Fig. 3(b), the loose rock continues to move downwards and, as it does so, further work is done on the support, the downward velocity of the rock layer is decreased, and the kinetic energy is thus converted to heat and other forms of dissipated energy in the support. In addition, as the loose rock moves downwards, it loses potential energy, and this is also capable of doing some work on the support.

If the support brings the hangingwall rock to rest, Fig. 3(c), after it has travelled downward some distance, say c (Wagner has suggested $c = 0{,}3\ m$ as a practical limit), it is possible to equate the energy absorbed by the support system to the energy lost by the hangingwall rock. On this basis it is possible to derive a relationship between the height of rock that can be decelerated (and thus adequately supported) and the support resistance (in kN/m^2) for a particular velocity v, assuming yielding support and a given amount of closure that can be tolerated during the rockburst. Such a relationship is shown in Fig. 4.

The Concept of Support Resistance

Support resistance is a useful parameter that gives an indication of the resistance of a support system to defor-

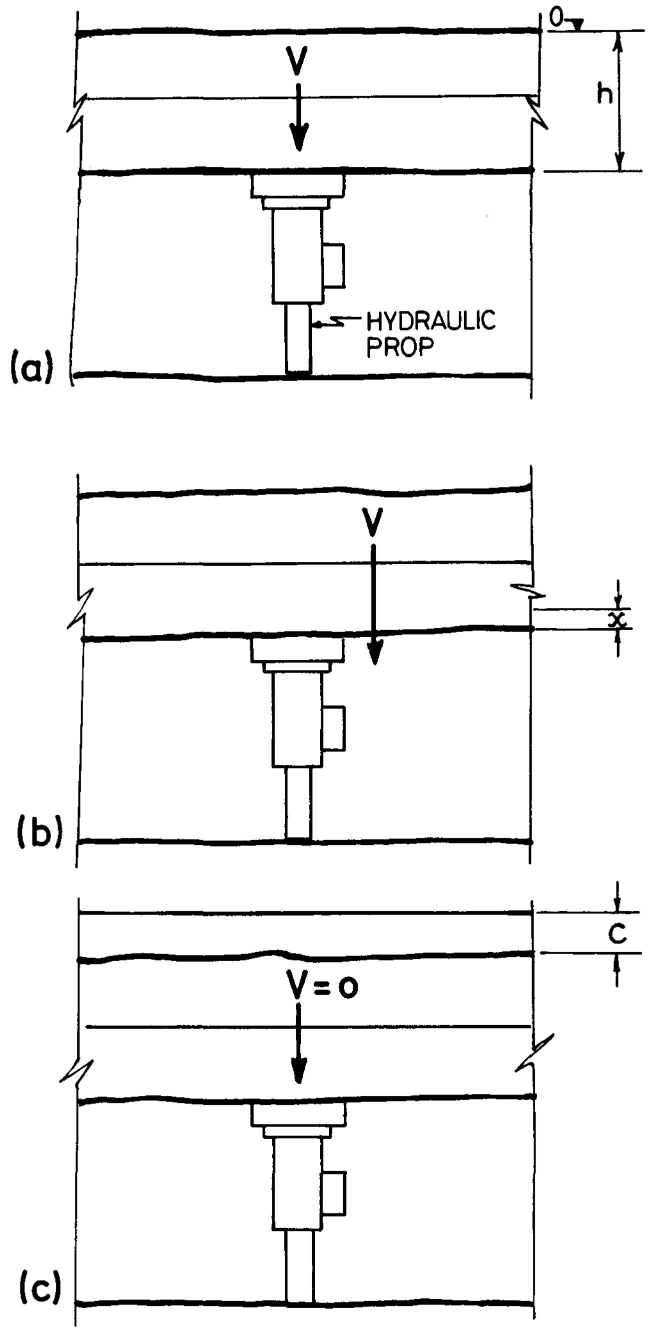

Fig. 3—Support reaction to a rockburst

(a) Loose rock starts to accelerate and reaches a maximum velocity, *v*

(b) Loose rock continues to move downwards. It decelerates as kinetic energy is absorbed by the work done on the support

(c) Loose rock has come to rest and is displaced by amount *c*

mation. Support resistance is a function of the spacing of support units and their load deformation characteristics, and can be defined as

$$SR = F_y . SD \text{ (kN/m}^2\text{)},$$

where F_y is the yield force of support units in kilonewtons and SD is the support density in support units per square metre².

The support resistance can be used in both stopes and tunnels in evaluations of a support system's ability to support various thicknesses of rock at different ground velocities.

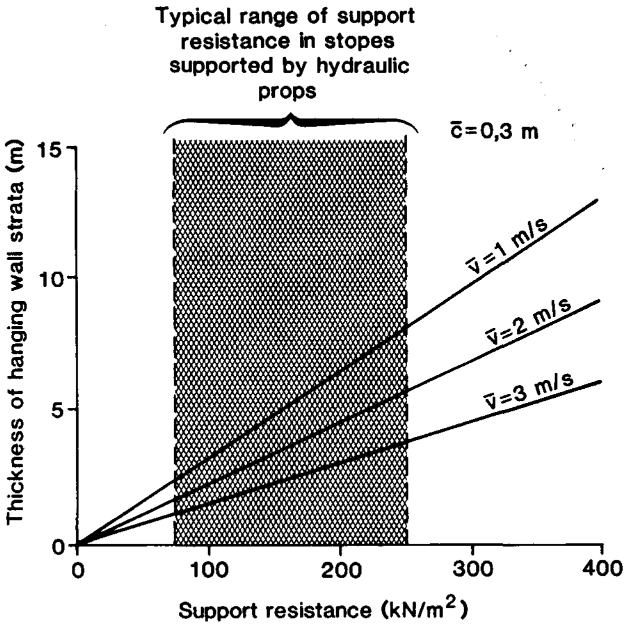

Fig. 4—The thickness of hangingwall strata that can be supported at different ground velocities as a function of support resistance (after Wagner[2])

Stope-support Systems during Rockbursts

Various types of stope-support systems are used in South African gold mines. Most common are yielding timber props and various types of packs. Backfill is less common, but its use is increasing.

In situ examination of the behaviour of these support systems after a rockburst can give many valuable insights to their effectiveness under different mining and geological conditions. Useful conclusions can be drawn from these underground observations, and mine managements and rock-mechanics practitioners have a wealth of knowledge to draw upon.

One of the ways of evaluating a support system is to consider how the support resistance changes from the point of installation to positions towards the back areas. Fig. 5 shows the support-resistance profile of a typical yielding timber prop-support system, a sandwich-pack system, and a backfill system as a function of the distance behind the face on strike. The spacing of the support units is considered typical of many stopes in the mining industry. The rate of stope closure is assumed to be 10 mm per metre of face advance. It can be seen that the resistance builds up slowly in the case of the pack and backfill systems. In the case of the yielding timber prop system, the support resistance rapidly increases to 100 kN/m² but does not exceed this since the timber props are designed to yield with constant force. In all three types of support, the support resistance is 100 kN or less in the face area. For example, reference to Fig. 4 shows that, for this support resistance, at most 2,0 m of hangingwall can be supported during a rockburst in which the ground velocity is 2 m/s. The support resistance can be increased if the spacing of the support units is decreased or if the stiffness of the backfill material is increased. In practice, economic considerations do not make this an attractive proposition. However, the use of hydraulic props can significantly increase the support resistance in the face area. The exact mode of interaction between hydraulic props and permanent support is not known, but in Fig. 6 the change in support resistance with distance from the face is plotted for a hypothetical integrated hydraulic-prop permanent-support system.

Wagner has argued that the damage associated with large seismic events can be controlled by increasing the support resistance. This is shown in Fig. 7, in which 3,0 m is assumed as the thickness of the separated strata. The areal extent of excessive stope-closure damage increases rapidly as the support resistance drops below 200 kN/m^2. For this reason, Wagner recommended that the support resistance in the face area should be not less than 200 kN/m^2. If Fig. 6 is considered, it is clear that, without the addition of hydraulic-prop support, common support systems do not provide this required support resistance in the face area. Thus, the importance of hydraulic-prop support in the face area and the consequent increase in support resistance cannot be overemphasized.

In weak or badly fractured rock, standard hydraulic props have been known to damage the hangingwall by punching into or otherwise fracturing the hangingwall rock during normal stope closure. As a result, during a rockburst, falls of hanging can occur between props. The use of a suitable headboard is therefore essential when hydraulic props are used in face areas under these conditions.

A useful comparison of the various stope timber-support systems can be obtained by a comparison of the energy that can be absorbed per unit area for each support system. This energy is related to the support resistance and to the amount that the support elements in the support system can deform. The examples of Fig. 8 are illuminating. For a stope closure of 0,1 m, the energy absorbed by pipe-stick support installed at a density of one unit per 2 m^2 is equivalent to that absorbed by a sandwich pack supporting 6 m^2. Alternatively, the energy absorbed by pipe-stick systems is four times that absorbed by a skeleton pack supporting an area of 6 m^2. It can be seen that the energy absorbed by the support system is strongly influenced by the spacing of the support units.

The use of backfill as a support medium is growing

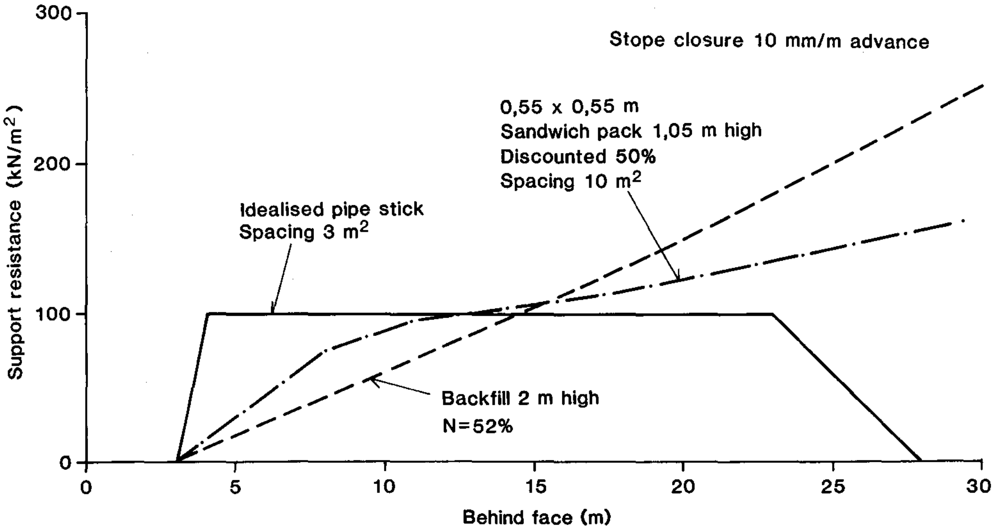

Fig. 5—The support resistance of various support systems as a function of distance behind the stope face

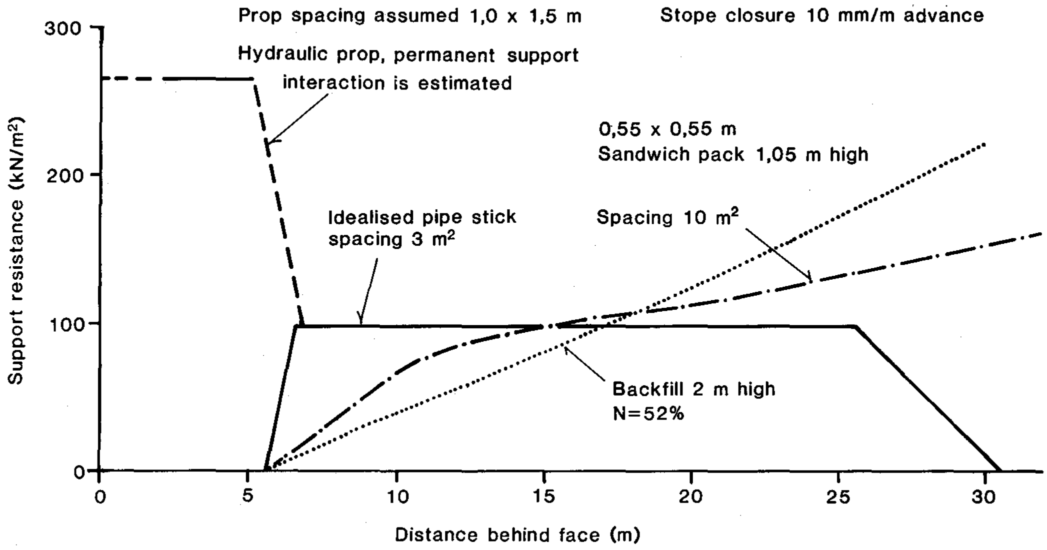

Fig. 6—The support resistance of various support systems integrated with hydraulic props as a function of distance behind the stope face

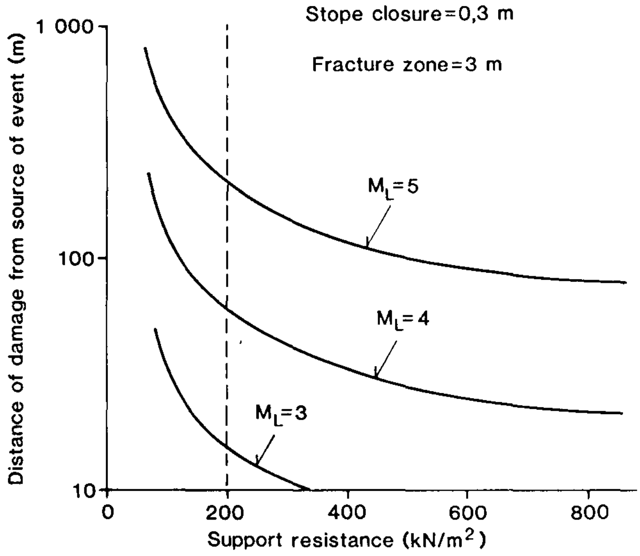

Fig. 7—Effect of support resistance on the areal extent of excessive stope closure caused by seismic events from magnitude 3 to 5 (after Wagner[2])

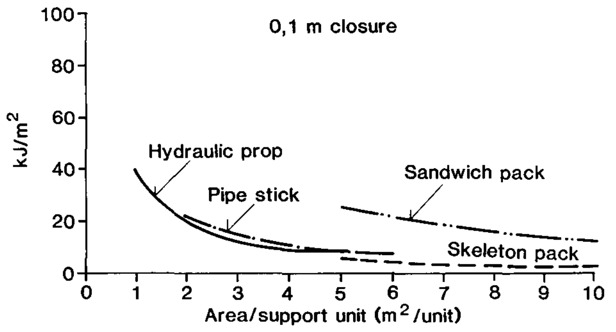

Fig. 8—Work done per unit area for different support systems as a function of support density (after Wagner[2])

in the mining industry. On placement close to the face, backfill is a relatively soft system, which needs to be supplemented with stiffer support units such as hydraulic props. However, because of its large areal coverage, backfill is able to provide very good support during rapid loading such as occurs during a rockburst since, as it converges, the stiffness of the fill increases dramatically and it is able to absorb considerable kinetic energy.

Observations in backfilled stopes that have experienced rockbursts support this statement. Considerable deformation of the backfill material was observed with very little stope damage.

Summary of Stope-support Requirements

(1) The ability of a support system to absorb energy is important. The spacing of support units determines the amount of energy absorbed by the system. A support system should be selected on the basis that it is able to absorb the maximum amount of energy at a spacing of support units that is cost-effective and that is within economic considerations.

(2) The support resistance must be as high as possible in the face area and, if practicable, should exceed 200 kN/m^2 as recommended by Wagner. This can be achieved by the integration of hydraulic props with the permanent support system.

(3) The use of a suitable headboard is often required in combination with hydraulic props to minimize punching damage to the hangingwall.

The Tunnel Environment

Of the tunnel development in South African gold mines, 80 per cent is associated with scattered mining[3]. These tunnels can be subject to large changes in field stress and sometimes to rockburst damage.

In common with stoping excavations, a zone of fractured rock surrounds each tunnel. Fig. 9 shows the extent of the fractured zone measured around a tunnel at Hartebeestfontein[4]. In severe cases, sidewall fracturing can be as deep as 6,0 m. Large deformations of the tunnel walls can occur by dilatation of the fractured zone around the tunnel, either over a long period of time or, in the case of a rockburst, very rapidly. The support system in a tunnel must be capable of supporting the fractured rock material constituting the tunnel walls. The system is also required to accommodate deformation of the tunnel sidewall.

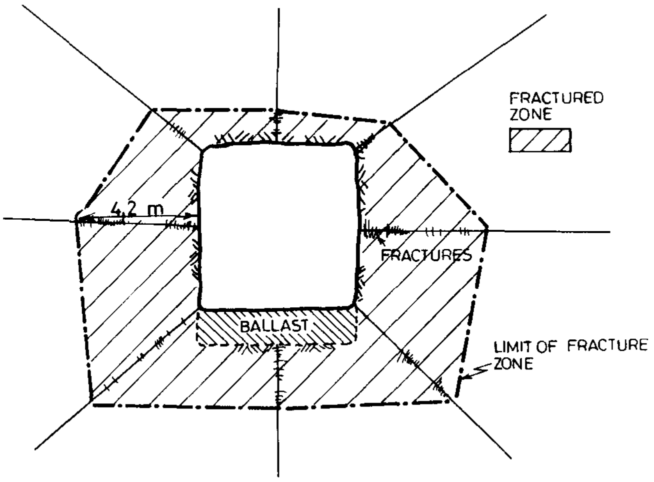

Fig. 9—A typical fracture pattern around a tunnel in a deep gold mine

Many techniques have been used in the support of gold-mine tunnels; sets and steel arches were particularly common a number of years ago. These support systems were intended to resist tunnel deformation and were not always satisfactory. In widespread use today are support systems that assist the fractured rock to support iself and are able to accommodate some deformation. These support systems are grouted bars, ropes, or studs that are integrated with a system of wire mesh and rope lacing.

The Design of Tunnel Support

Measurements of peak ground velocities were made recently in the solid rock in the sidewall of a tunnel at Hartebeestfontein[5]. A typical waveform is shown in Fig. 10, and Table I lists measurements during four small rockbursts.

During the first event shown in Table I, damage occurred at the site of the accelerometers but, during the last three events, no major damage was observed at the recording site although damage occurred at other points in the tunnel. In this particular situation, it would ap-

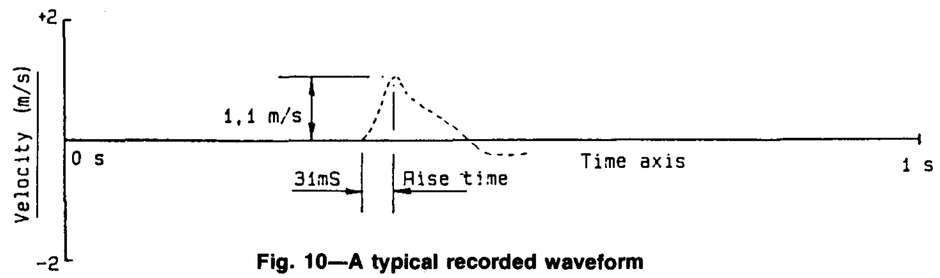

Fig. 10—A typical recorded waveform

TABLE I
PEAK GROUND VELOCITIES AT HARTEBEESTFONTEIN

Magnitude of event	Distance to event, m	Peak velocity (v_p), m/s	Rise time (R) ms
2,5	70	1,10	31
2,5	204	0,11	36
1,9	180	0,14	25
2,5	130	0,17	22

pear that peak ground velocities of more than 1 m/s are necessary to cause damage in tunnels supported in a similar way to the damaged tunnel (2,2 m grouted shepherd's crooks at 1,5 m diamond pattern with mesh and lacing). Lower ground velocities have been observed to cause damage in other tunnels[6].

An analysis of the recorded waveform showed that the peak velocity occurred at a frequency of 8,3 Hz. The instrument was capable of measuring frequencies up to 20 Hz. This frequency compares favourably with the data quoted by Hendron and Fernandez[1] for the San Fernando earthquake of 1971, where peak ground velocities occurred at a frequency in the range of 10 Hz. It is interesting to note that the wave front (assuming a velocity of 5,4 km/s) could have travelled a distance of about 160 m during the time taken for the particle velocity to reach its peak value.

The seismic data shown in the Addendum for the first event of Table I were used to derive lateral forces on the fractured rock that amount to about 5,7 g (9,81 m/s^2). The forces on the fractured rock caused by gravity and by the seismic wave on the fractured rock are as shown in Fig. 11.

There are two alternative strategies for the design of support in such a tunnel.

Firstly, one could try to prevent the loose rock from parting company with the intact elastic rockmass. In order to do this, it is necessary to provide support for the acceleration forces of 5,7 g as shown in Fig. 12. For a depth of sidewall fracturing of 4 m, the support resistance required would be approximately 600 kN/m^2. This would appear to be impracticable using present technology.

The second course of action is to permit the loose rock to be accelerated away from the intact elastic rockmass. In this case, the loose rock will attain some velocity, v, and therefore some kinetic energy, $\frac{1}{2}mv^2$. The purpose of the support will now be to absorb this kinetic energy. Yielding support is thus required, since this type of support is capable of absorbing far more energy than simple end-anchored rockbolts. Wagner[2] used a similar argument to derive the depth of sidewall rock that can be supported for a given velocity. This is described in the next section of this paper.

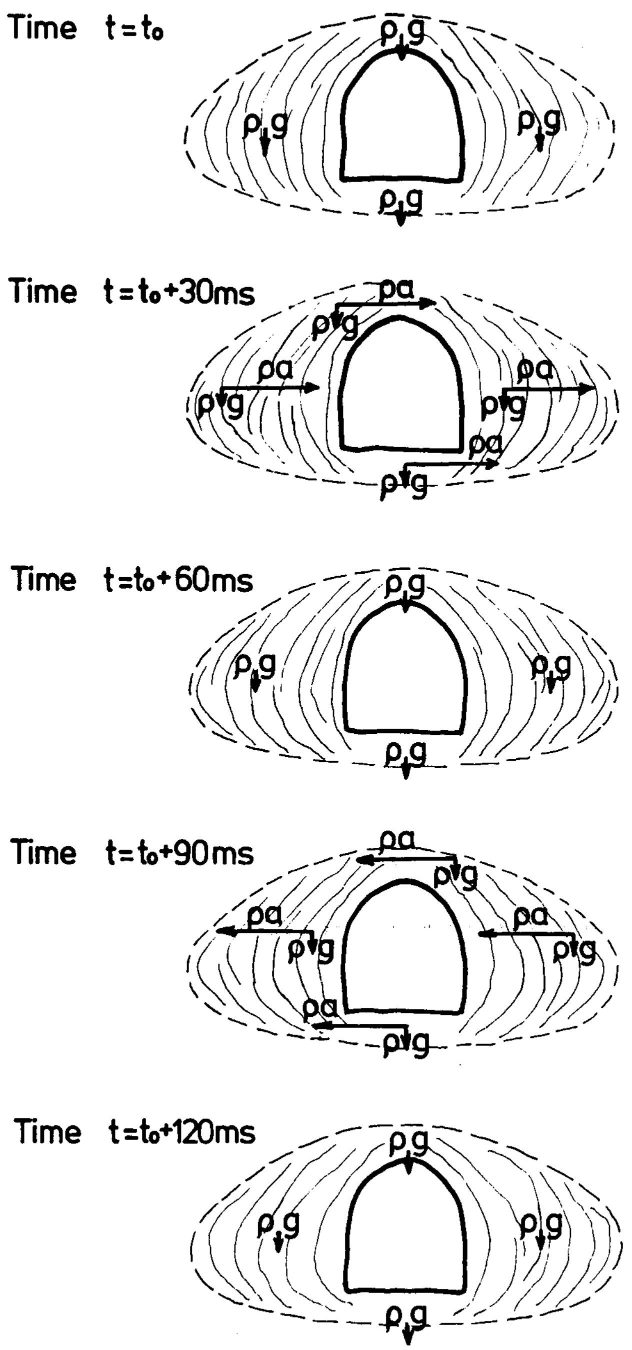

Fig. 11—Forces on fractured rock due to gravity and the assumed sinusoidal seismic wave

Tunnel Support during Rockbursts

As with stope support, the *in situ* examination of tunnel support systems that have been damaged by rock-

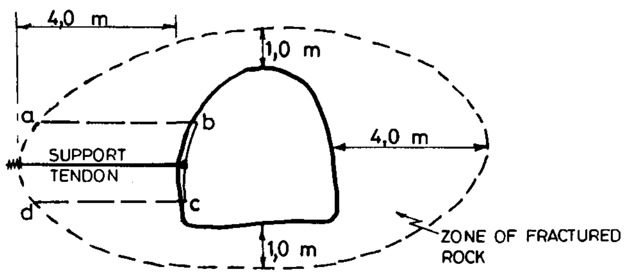

Fig. 12—Hypothetical method of tieing fractured rock to elastic rock

bursts gives valuable information as to the effectiveness of these systems. However, the performance of a support system during a rockburst cannot be deduced from underground observations alone. Wagner[2] considered this problem in terms of the work that the deforming tunnel wall does on a tendon, as well as the support resistance required to contain the rockmass.

The load displacement behaviour of end-anchored bolts and grouted rope is shown in Fig. 13. Yield occurs at approximately 100 kN, following which the bolts can withstand deformations of up to only 30 mm before failing. The work done during yielding is approximately 2 kJ for a grouted tendon of 16 mm diameter and 2 m length (Fig. 14).

The inability of tendons to yield is not always apparent when observed underground. They are usually integrated with a system of mesh and lace, which allows the fractured rock material, confined by the mesh and lace, to deform around the tendons. The integrated tendon, mesh, and lace system, therefore, does allow some tunnel deformation—certainly more than the deformation characteristics of the tendon alone. At a mine in the Klerksdorp area, a deformation of 500 mm of the mesh and lace was measured between support tendons. The mesh and lace had contained the fractured material and allowed it to deform around the tendons.

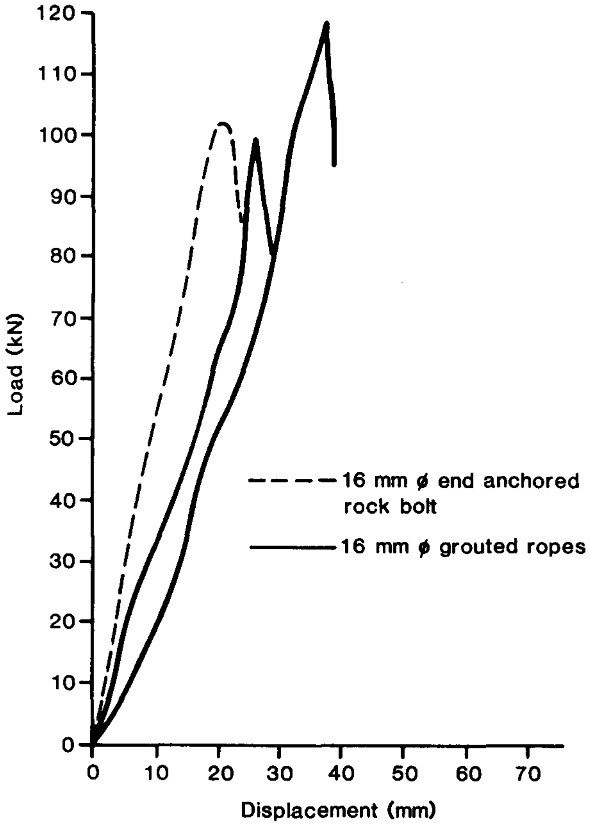

Fig. 13—Load deformation characteristics of different support tendons (after Wagner[2])

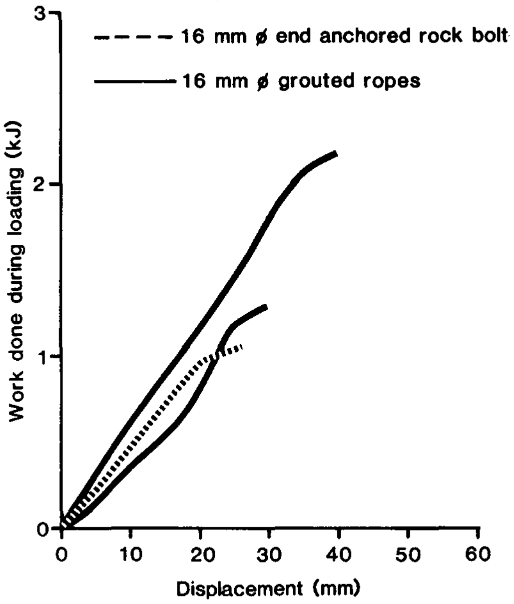

Fig. 14—Work done by support tendons during loading (after Wagner[2])

Typically, the support density in a gold-mine tunnel varies from 0,6 to 1,6 (units per square metre of tunnel). This corresponds to a support resistance of 60 to 160 kN/m^2 for a yield load of 100 kN per tendon. Fig. 15 relates the thickness of a sidewall slab that can be supported at various ground velocities as a function of support resistance. For example, at a support resistance of 160 kN/m^2, a support system can support a sidewall slab 1,25 m thick with a ground velocity of 1 = m/s. At a ground velocity of 2 m/s, a slab of 0,25 m can be supported. This illustrates the vulnerability of a support system to increasing ground velocities.

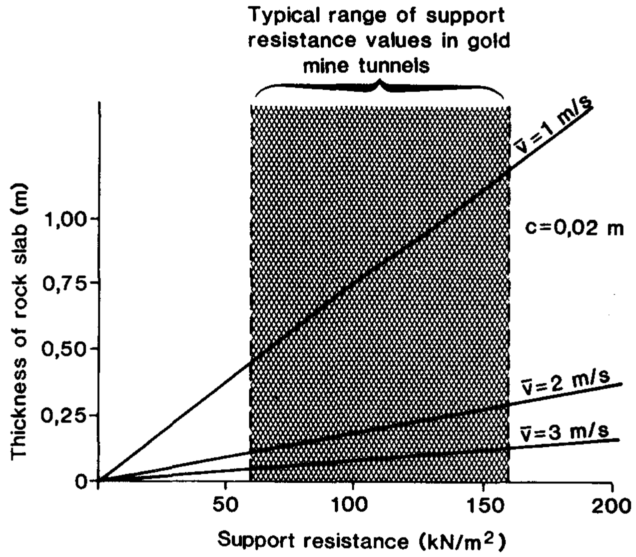

Fig. 15—The width of fracture zone in the sidewall of a tunnel that can be supported at different ground velocities as a function of support resistance (after Wagner[2])

Wagner has shown that the limited ability of these tendons to absorb energy implies that the potential areal extent of damage to tunnels is larger than that to stopes subjected to the same seismic event. In addition, if the support resistance falls below about 60 kN/m^2, the areal extent of damage increases markedly. Theoretically, a yielding tendon that has the same yield load as conventional tendons is able to absorb five times as much energy and is therefore able to reduce the areal extent of damage as shown in Fig. 16. The principle of the yielding tendon is that it is able to absorb energy and yield at a force lower than the force that would cause it to fail completely.

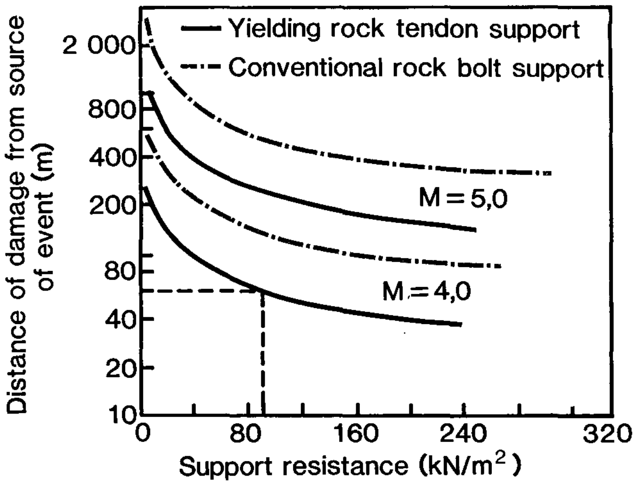

Fig. 16—Effect of the improved yield characteristics of support tendons on the areal extent of tunnel damage from seismic events with a magnitude ranging from 2 to 5—the thickness of the fracture zone in the tunnel walls is 0,5 m (after Wagner[2])

The advantages of a yielding tendon are clear. This concept is currently being researched by the Chamber of Mines of South Africa Research Organization.

Summary of Tunnel-support Requirements

(1) The support resistance of a tunnel-support system should not be lower than 60 kN/m^2.

(2) The ability to yield and to absorb energy while yielding is an important characteristic that is required of a tendon.

(3) While yielding, a support system should maintain the integrity of the fractured rock material making up the tunnel walls.

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Addendum: Derivation of Forces from Seismic Information

If the waveforms are approximately sinusoidal during an event (Fig. 10), the dynamic forces on the fractured rock can be found as follows:

$$\text{Displacement } x = a \sin(wt) \quad \text{(A1)}$$

$$\text{Velocity } \dot{x} = wa \cos(wt) \quad \text{(A2)}$$

$$\text{Acceleration } \ddot{x} = -w^2 a \cos(wt). \quad \text{(A3)}$$

From the rise time of 31 ms, the value of w can be found. The maximum velocity (wa) was measured at 1,1 m/s:

$$w = \frac{2\pi}{4{,}31 \cdot 10^{-3}} = 51 \text{ rad/s}. \quad \text{(A4)}$$

The maximum acceleration can thus be found:

$$\begin{aligned} \ddot{x}_{\max} &= wa \cdot w \\ &= 1{,}1 \cdot 51 \\ &= 56 \text{ m/s}^2. \end{aligned}$$

This represents about 5,7 g.